SECTION 4
ELECTROMAGNETIC COMPATIBILITY ANALYSIS

4.1 INTRODUCTION

This section contains analysis procedures for determining the separation distances between radar stations and earth stations necessary to mitigate interference due to receiver front-end overload and radar transmitter spurious emissions. The separation distances are based on radar station and earth station characteristics associated with regulatory standards contained in Sections 2 and 3. Since nominal radar and earth station system characteristics and typical antenna heights are used in these calculations, the separation distance calculations presented in this section are to assess the potential for interference and to provide an estimate of when a detailed electromagnetic compatibility (EMC) analysis may be required.

A smooth-earth propagation model, NLAMDA[13] (NA), was used to calculate the required separation distances presented in this section. For detailed EMC analyses, a propagation model that takes into consideration the terrain (such as TIREM14) between the radar station and earth station should be used in determining the propagation loss. Also, building attenuation, foliage attenuation, and ducting should be considered in determining the propagation loss.

In addition, when performing a detailed EMC analysis, it is also necessary to perform an analysis for indirect path coupling (multiple path scattering). When the direct path between a transmitter and a receiver contains propagation obstacles, multiple path scattering caused by terrain or building reflections can result in significantly less propagation loss than along the direct path. Such multiple path propagation can also cause an apparent stretching of radar pulses. The effect of such stretching is to increase the time interval of the interference, thus increasing the potential degradation to an earth station.

4.2 RADAR STATION CHARACTERISTICS

The following are nominal characteristics of radar stations operating in the 2700- to 3700-MHz bands. These characteristics are identified for the purpose of EMC analysis.

Peak Transmit Power (P_T)	=	0.86 to 4.0 MW (+89 to +96 dBm), nominal +90 dBm
Main Beam Gain (G_T)	=	30 to 34 dBi, nominal 32 dBi
Pulse Width	=	1 to 60 μs
Pulse Repetition Rate	=	100 to 27,000 pps
Duty Cycle	=	0.1 to 6 percent

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13 M.A. Maiuzzo and W.E. Frazier, "A Theoretical Groundwave Propagation Model - NJ Model, " DOD Electromagnetic Compatibility Analysis Center (ECAC), December 1968.

14 G. Benoit, "Terrain-Integrated Rough-Earth Model (TIREM) Handbook," ECAC-HDBK-86-076, DOD Electromagnetic Compatibility Analysis Center, September 1986.

4.3 EARTH STATION CHARACTERISTICS

Table 4 summarizes the nominal characteristics of earth stations in the 4-GHz band associated with TVRO and audio receive only (ARO) terminals. Currently there is a mix of analog and digital earth station systems in the 4-GHz band with a majority of the TVRO earth stations using analog frequency modulation (FM). However, there is a trend toward use of digital modulations. The susceptibility of these digital modulations to pulsed emissions is a function of the order of digital modulation used (i.e., BPSK, QPSK, etc.). Manufacturers of 4-GHz earth stations have indicated that digital modulation systems are more susceptible to interference than analog systems.

TABLE 4.
CHARACTERISTICS OF 4-GHz EARTH STATION RECEIVER SYSTEMS

	Analog Television Receive-Only (TVRO) Systems	Digital Television Receive-Only (TVRO) Systems	Digital Audio Receiver Terminals (DART)
Modulation	FM	QPSK	BPSK
Receive Frequency, MHz	3700-4200	3700-4200	3700-4200
Antenna Main Beam Gain, dBi	40 to 44 @ 4.0 GHz, nominal 42	40 to 44 @ 4.0 GHz, nominal 42	40 to 44 @ 4.0 GHz, nominal 42
Antenna Output Level, dBm	-105 to -95, nominal -100	-105 to -95, nominal -100	-105 to -95, nominal -100
Receiver Input Frequency, MHz	270 to 770 (LNC) 950 to 1450 (LNB)	950-1450 (LNB)	270
Number of Channels	24*	24*	20 @ 384 kbps****
Receiver Input Level, dBm	-70 to -30	-65 to -25	-65 to -45
IF Bandwidth, MHz	30**	15 to 31***	20
Maximum Receiver Noise Figure, dB	12	12	12
Maximum Bit Error Rate (BER)	N/A	10^{-6}	10^{-3}
Error Correction	N/A	Yes	Yes, 7/8 code rate
Minimum Carrier-to-Noise Ratio (C/N), dB	N/A	7.5	6
Protection Ratio (C/I), dB	10	12	12

* 12 channels on vertical feed and 12 channels on horizontal feed
** Adjacent channel rejection achieved by polarization discrimination
*** Depending upon receiver mode
**** Time-division multiplexed (TDM)

4.4 RECEIVER FRONT-END OVERLOAD INTERFERENCE

Due to the high power levels required to cause receiver front-end overload in a 4-GHz earth station, it is likely that radar interference will occur only when the main beam of a radar is directed at the earth station site. Also, based on the results of NTIA front-end recovery tests (Figures 8 through 10), gain compression will occur in coincidence with each pulse in the radar main beam, with a finite recovery time that varies with the amount of gain compression and type of LNA/LNB amplifier. As shown in Figures 8 through 10, the gain compression from each pulse may last as little as about 1 us (the pulse width of the radar) or may approach the entire interval between pulses (see the 40-dB gain compression curve in Figure 8). In summary, the effects of earth station front-end overload interference will be a function of the degree of gain compression and the radar pulse repetition rate.

As a radar antenna main beam scans across an earth station, approximately 20 pulses will typically be directed at that station. The operational characteristics of 2700- to 3700-MHz radars are such that each pulse will be about 1-60 us long, and the spacing between pulses will usually be about 1-3 ms, although much shorter intervals, on the order of tens of microseconds, are possible for some radars. If the radar main beam is utilized in a mechanically scanned rotation, then it will sweep across the earth station site at very precise and regular intervals of typically 5-15 s. (Some radars scan electronically in elevation while rotating mechanically, and thus the interval for such radars may appear slightly irregular.) If the radar utilizes a phased array antenna, then the main beam will still probably be directed at the earth station every few seconds, but the exact interval between visitations will be irregular.

For analog TVRO systems, these interference bursts may be observed on a television screen as a pattern of black or white spots. For earth stations using digital systems (television or audio), the performance degradation will be manifested as an increase in bit error rate (BER) for slight gain compression, to loss of sync (out-of-frame) for severe (long recovery time) gain compression. Because of the potential for loss of sync, the potential performance degradation of digital systems may be more catastrophic than for analog systems, thus increasing the susceptibility of digital systems to pulse-type emissions and reported interference cases.

4.5 SEPARATION DISTANCE REQUIRED TO PRECLUDE OVERLOAD INTERFERENCE

The following is a discussion of the procedure to determine separation distance between radar stations and earth stations to ensure compatibility for receiver front-end overload coupling. To determine the separation distance it is necessary to calculate the propagation loss required to preclude interference to an earth station receiver system. For direct path coupling, the required propagation loss is given by

$$L_p = P_T + G_T + G_R(\Theta) - L_T - L_R - I_{MAX} \quad (5)$$

Where:

L_p	=	**Median propagation path loss between the transmitting and receiving antennas, in dB.**
P_T	=	**Peak transmitted power of radar station, nominal +90 dBm.**
G_T	=	**Radar station main beam antenna gain, nominal +32 dBi.**
$G_R(\Theta)$	=	Earth station antenna gain in the direction of the radar station, nominal $32 - 25 \log_{10}(\Theta)$ dBi for $1° \leq \Theta \leq 48°$ and -10 dBi for $48° < \Theta \leq 180°$ (CFR Title 47, § 25.209).
L_T	=	**Insertion loss in the radar station transmitter, in dB (assumed 2 dB).**
L_R	=	**Insertion loss in the earth station receiver system, in dB (assumed O dB)**
I_{MAX}	=	**Maximum radar signal level at the antenna output which precludes receiver front-end overload (See Equation 4), nominal -50 to -40 dBm.**

When the required propagation loss is determined, an appropriate propagation model must be applied to determine the nominal separation distance between radar stations and earth stations at which it may be necessary to perform a detailed analysis. For this analysis, the NLAMDA (Nλ) propagation model was used to estimate the distance for the required basic transmission loss.

The required separation distance between a radar station and earth station to preclude interference due to receiver front-end overload for an airborne radar platform and a surface radar station is shown in Figure 17. The separation distance is shown as a function of off-axis angle of the earth station antenna. The altitude, H_t, of the airborne radar was set at 10,000 m, and the antenna height used for the surface radar was 25 m. The earth station antenna height, H_r, was set at 4 m. The separation distance to preclude receiver front-end overload from airborne radars is several hundred kilometers even at off-axis angles greater than 10 degrees. For surface radars, front-end overload interference may occur at ranges of 60 km for a few degrees off-axis to less than 40 km for off-axis angles greater than 30 degrees. Note that, with RF filter installation **ahead** of the LNA as described in Sections 3.3 and 3.5, the separation distance required to preclude front-end overload would become negligible.

4.6 RADAR TRANSMITTER SPURIOUS EMISSIONS INTERFERENCE

Due to the relative level of radar spurious emissions to the radar fundamental emissions, it is likely that radar interference due to spurious emissions will occur only when the main beam of a radar is directed at the earth station site. As previously discussed, approximately 20 pulses will typically be directed at the earth station as the radar antenna main beam scans across the earth station. To determine the effect of this pulse train associated with spurious emissions from radar stations on earth station receiver system performance, it is necessary to characterize the pulse time waveform responses in the receiver IF passband.

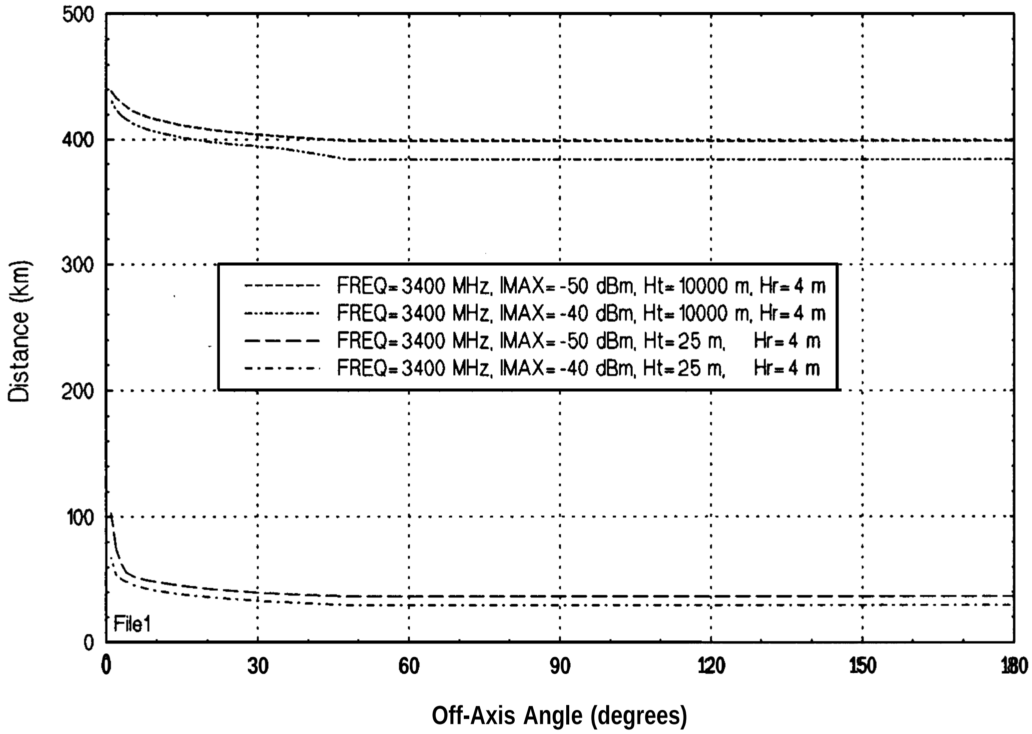

Figure 17. **Separation distances required to preclude earth station front-end overload by radar fundamental, as a function of I_{max} and antenna height. See text for station parameters.**

Figures 18-19 show pulse time waveform measurements at the radar fundamental frequency (reference pulse width) as well as at other frequencies in the 4-GHz band. These measurements were made with the RSMS front-end (RF preselector through IF output) and a digital oscilloscope. The time waveforms indicate that the radar spurious emissions in the 4-GHz band produce two types of time waveform response at the receiver IF output:

1) spurious emissions produced from the pulse modulation leading edge and trailing edge

2) spurious emissions produced by the radar output device inherent noise during the pulse interval.

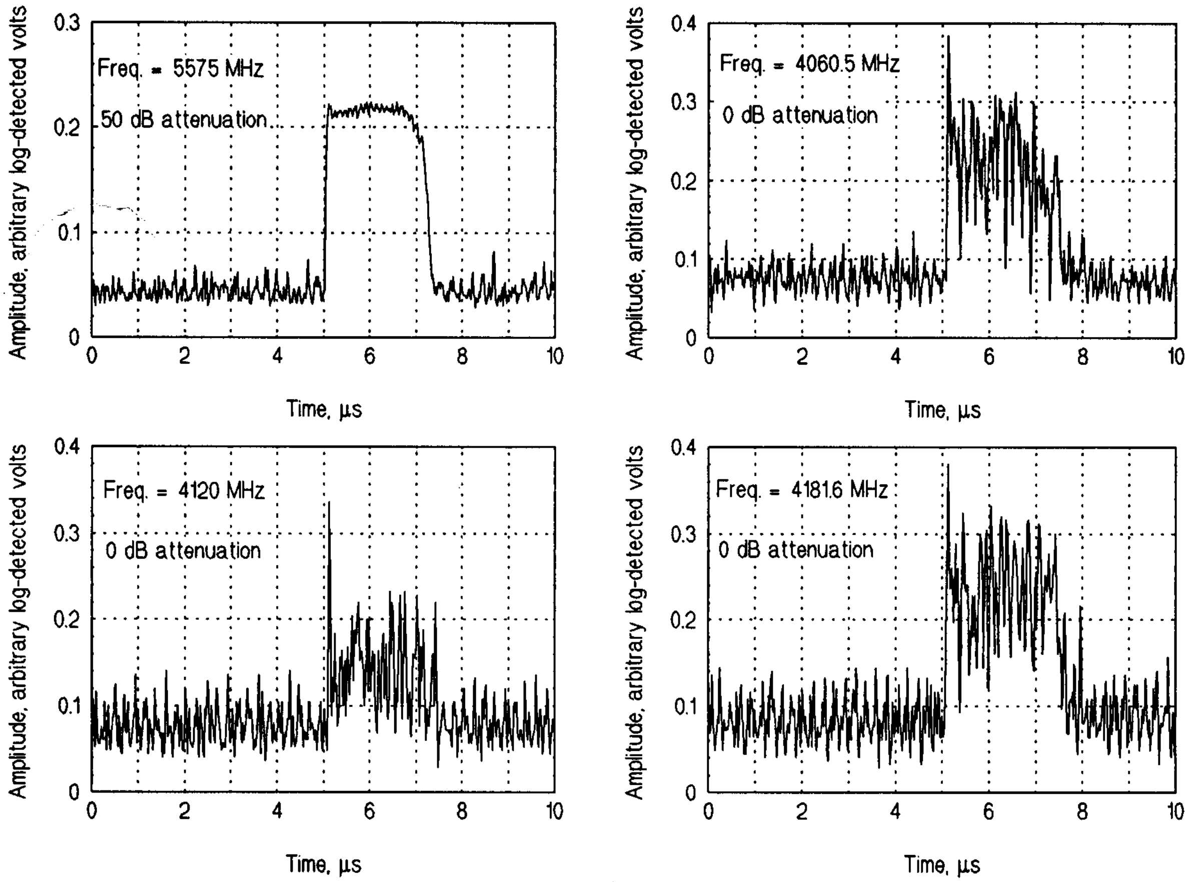

Figure 18. **Time waveforms of a weather radar at center frequency (5575 MHz) and at three frequencies in the 3700- to 4200-MHz band. Radiated measurement in 3-MHz bandwidth.**

Effects of Radar Spurious Emissions

The spurious emissions occurring during the leading and trailing edges of the pulses are broadband in nature, thus producing an impulse response in the earth station receiver IF output. The amplitudes of the leading and trailing edge impulse responses are not always equal, and some received pulses may lack a leading or trailing edge altogether. Because the actual widths of the leading and trailing edge features are often only a few nanoseconds, the apparent widths of these impulse responses in the receiver are a function of the reciprocal of the receiver IF bandwidth (that is, they are bandwidth-limited in the receiver). Therefore, leading and trailing edge impulse responses will appear to be approximately 30 to 50 ns for nominal IF bandwidths used by 4-GHz earth stations. Thus, the leading and trailing edge impulse responses appear as short pulses approximately equal to a baud interval of a digital system. The effect of these receiver impulses on digital systems is to cause background or residual error rates.

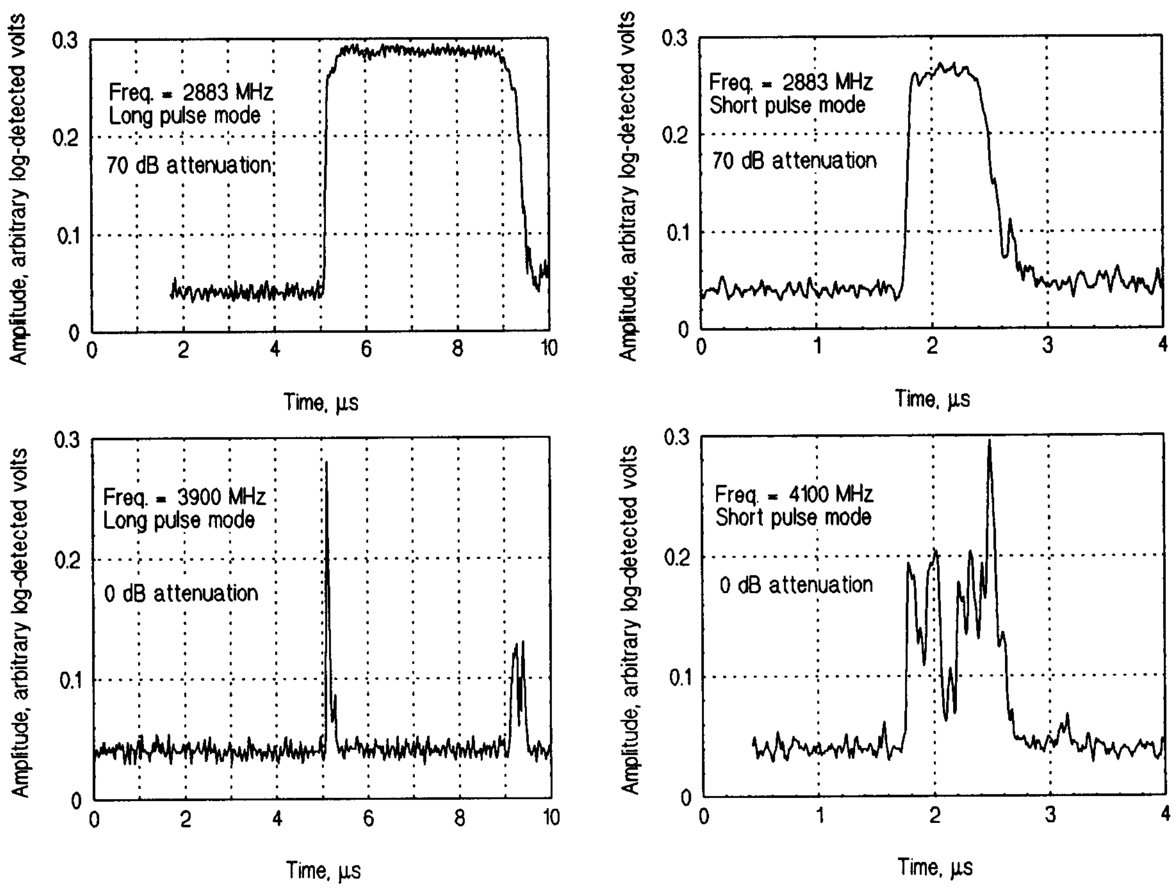

Figure 19. **Time waveforms of radar in two pulse modes (long and short) at center frequency (2883 MHz), and at two frequencies in the 3700- to 4200-MHz band. Radiated measurement in 3-MHz bandwidth.**

Radar spurious emissions occurring between the leading and trailing edges of the pulses will appear at the receiver IF output as non-coherent noise. The duration of such noise in a pulse may be equal to or shorter than the nominal pulse width. If the noise pulses are approximately equal in length to the nominal radar pulse width (which may be at least several microseconds), and are at amplitudes that exceed the earth station C/I protection ratio, then error rates momentarily above the earth station maximum bit error rate (BER) may occur. Also, when the full noise pulse duration exceeds the required protection ratio, the noise may defeat the receiver error correction function and result in a block of errors for each incoming pulse.

If the radar spurious emissions produce pulses at the receiver if output for several framing pulses in digital systems, system out-of-frame condition will occur. The reframe interval may last for tens of milliseconds and will inevitably cause a severely errored second. Error correction provides no advantage when out-of-frame condition occurs. Generally, for

radar spurious emissions to cause out-of-frame in digital systems, multipath scattering (pulse stretching) must occur, so as to stretch the received pulse length to exceed several framing intervals.

4.7 SEPARATION DISTANCE REQUIRED TO PRECLUDE SPURIOUS EMISSIONS INTERFERENCE

As mentioned earlier, the level of radar spurious emissions is a function of the type of radar transmitter output device (see Table 3). The first step in assessing the potential for interference due to radar spurious emissions should be to identify the type of output device used in the radar of concern. The separation distances presented in this section are only applicable to radars using magnetrons or coaxial magnetron output devices.

The following is a discussion of the procedure to determine the separation distance between radar stations and earth stations to ensure compatible operation of the radar and earth station systems. To determine the distance from a radar station at which it may be necessary to perform such an analysis, it is necessary to determine the required propagation loss that will ensure compatibility. For direct path coupling, the required propagation loss is given by

$$L_p = (C/I) - C + P_T + G_T + G_R - L_T - L_R - FDR \qquad (6)$$

Where:

L_p	=	Median propagation path loss between the transmitting and receiving antennas, in dB.
C/I	=	Carrier-to-interference ratio at the predetector input (IF output) necessary to maintain acceptable performance criteria, nominal +12 dB.
C	=	Received carrier level at earth station antenna output, nominal -100 dBm.
P_T	=	Peak transmitted power of interfering radar station, nominal +90 dBm.
G_T	=	Interfering radar station main beam antenna gain, nominal +32 dBi.
$G_R(\Theta)$	=	Earth station antenna gain in the direction of the interfering radar station, nominal $32 - 25\log_{10}(\Theta)$ dBi for $1° \leq \Theta \leq 48°$ and -10 dBi for $48° < \Theta \leq 180°$ (CFR Title 47, § 25.209).
L_T	=	Insertion loss in the radar station transmitter, in dB (assumed 2 dB).
L_R	=	Insertion loss in the earth station receiver system, in dB (assumed 0 dB).

FDR = Frequency-dependent rejection of spurious emissions between the radar transmitter and the earth station receiver system, in dBc. Nominal +60 to +80 dB -10 log(BWIF(MHz)/(1 MHz)). (60 to 80 dBc represents worst-case RSEC and nominal magnetron/coaxial magnetron spurious emission levels in a 1-MHz bandwidth; see Table 3.)

BWIF = Earth station receiver intermediate frequency (IF) bandwidth, nominal 30 MHz.

After the required propagation loss was determined, the NLAMDA propagation model was applied to determine the nominal separation distance between radar stations and earth stations at which radar transmitter spurious emission interference would be precluded. At separations less than that distance, it may be necessary to perform a detailed analysis.

The required separation distances between a radar station and an earth station to preclude interference due to radar transmitter spurious emissions for surface radar stations are shown in Figure 20. The separation distance is shown as a function of off-axis angle of the earth station antenna. The radar antenna heights, H_t, used were 25 m and 9 m. (There have been no substantiated cases of radar spurious emission interference from airborne radars to 4-GHz earth stations; therefore, an antenna height of 10,000 m was not used.) The earth station antenna height, H_r, was set at 4 m. The separation distance required to preclude radar transmitter spurious emission interference ranges from several hundred kilometers at off-axis angles of less than 5 degrees to less than 50 km for off-axis angles greater than 30 degrees.

4.8 SUMMARY OF ELECTROMAGNETIC COMPATIBILITY ANALYSIS

In summary, there are many radar station, earth station, and environmental factors that influence the effects of pulsed radar emissions on earth station receiver system performance and the resulting separation distance required to preclude interference. The analytical determination of these effects is very complex. Because of this complexity, every effort should be made to ensure compatibility. Methods of mitigating interference between radars and earth stations are discussed in Section 3. The EMC analysis showed that interference from radar stations to 4-GHz earth stations can occur even if all current Federal standards for radars and earth stations are satisfied.

The separation distance to preclude front-end overload from airborne radars is several hundred kilometers even at off-axis angles greater than 10 degrees. For surface radars, front-end overload interference may occur at ranges of 60 km for a few degrees off-axis to less than 40 km for off-axis angles greater than 30 degrees. The separation distance required to preclude radar transmitter spurious emission interference ranges from several hundred kilometers at off-axis angles of less than 5 degrees to less than 50 km for off-axis angles greater than 30 degrees.

Although most radar types can accept the installation of an output filter to reduce spurious emissions, some radar systems utilize distributed, phased-array transmitters and thus cannot be effectively output filtered. Therefore, the required spurious emission attenuation

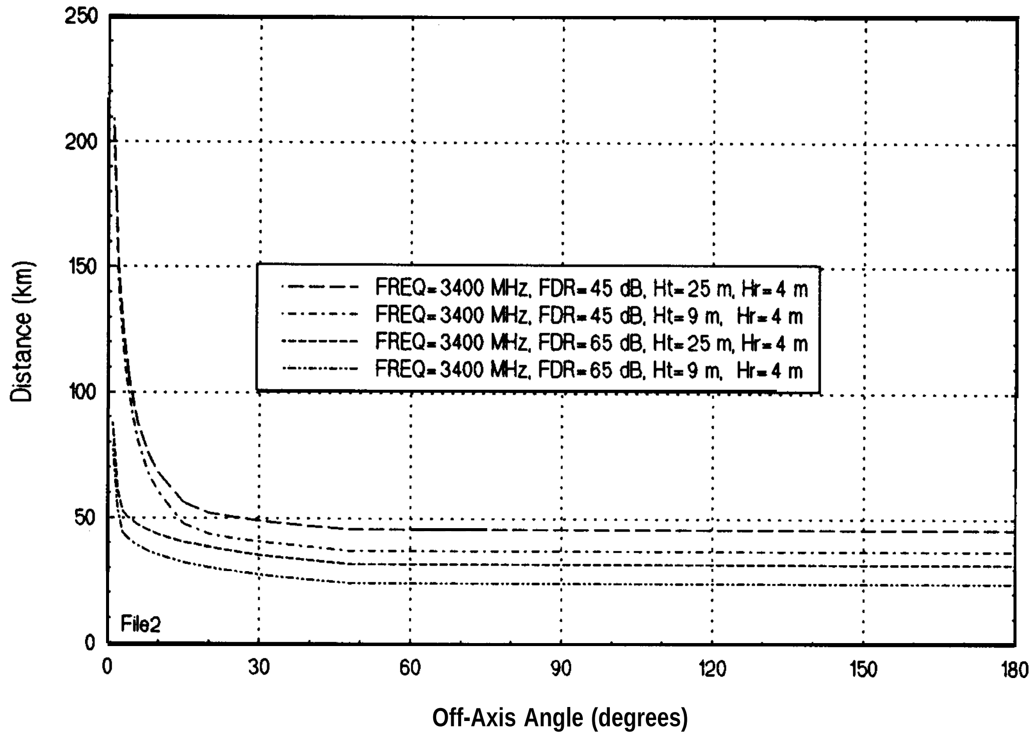

Figure 20. **Separation distance required to preclude earth station interference by radar spurious emissions, as a function of FDR and antenna height. Nominal station parameters used (see text).**

must be provided by one or more of these mitigation measures: improved earth station sidelobe suppression levels, or improved earth station antenna site selection.